NASA Proof-of-Concept 1-W Stirling Convertor Development for Small RPS

AIAA Propulsion and Energy (P&E) Forum and Exposition, International Energy Conversion and Engineering Conference (IECEC)

August 19-22, 2019, Indianapolis, IN

Session: ECD-02

Authors: Nick Schifer[1], Scott Wilson[1], Daniel Goodell[1], Michael Casciani[2]

1. NASA Glenn Research Center, 2. Vantage Partners, LLC

Why Low Power RPS?

Small nuclear power systems that would provide electricity to probes, landers, rovers, or communication repeaters for space missions

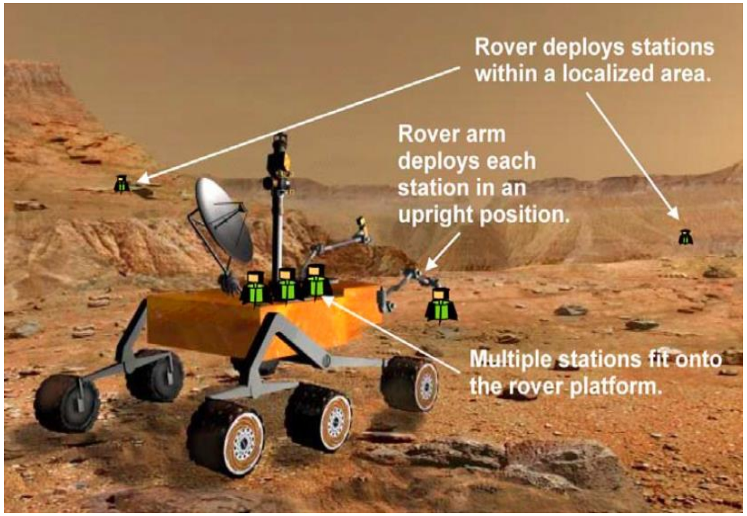
- Operate in vacuum or on planetary surface (ie. Moon, Mars, more...)
- Use conversion technology to convert heat to electricity for powering spacecraft sensors and communications
  - Fractional GPHS (General Purpose Heat Source) offers around 60 watts of thermal input
  - LWRHU (Light Weight Radioisotope Heater Unit, often called RHU) offers around 1 watt of thermal input for each unit and multiple units could be used

Development Goals

- Sufficient power for spacecraft functions
- Long-life and low degradation to ensure power at EOM
- Robust to critical environments (vibration, shock, constant acceleration, radiation)
- Thermal capability and high efficiency

Dynamic Power Conversion

- **12-16% overall system efficiency possible from 1 to 10 watts electrical power output**



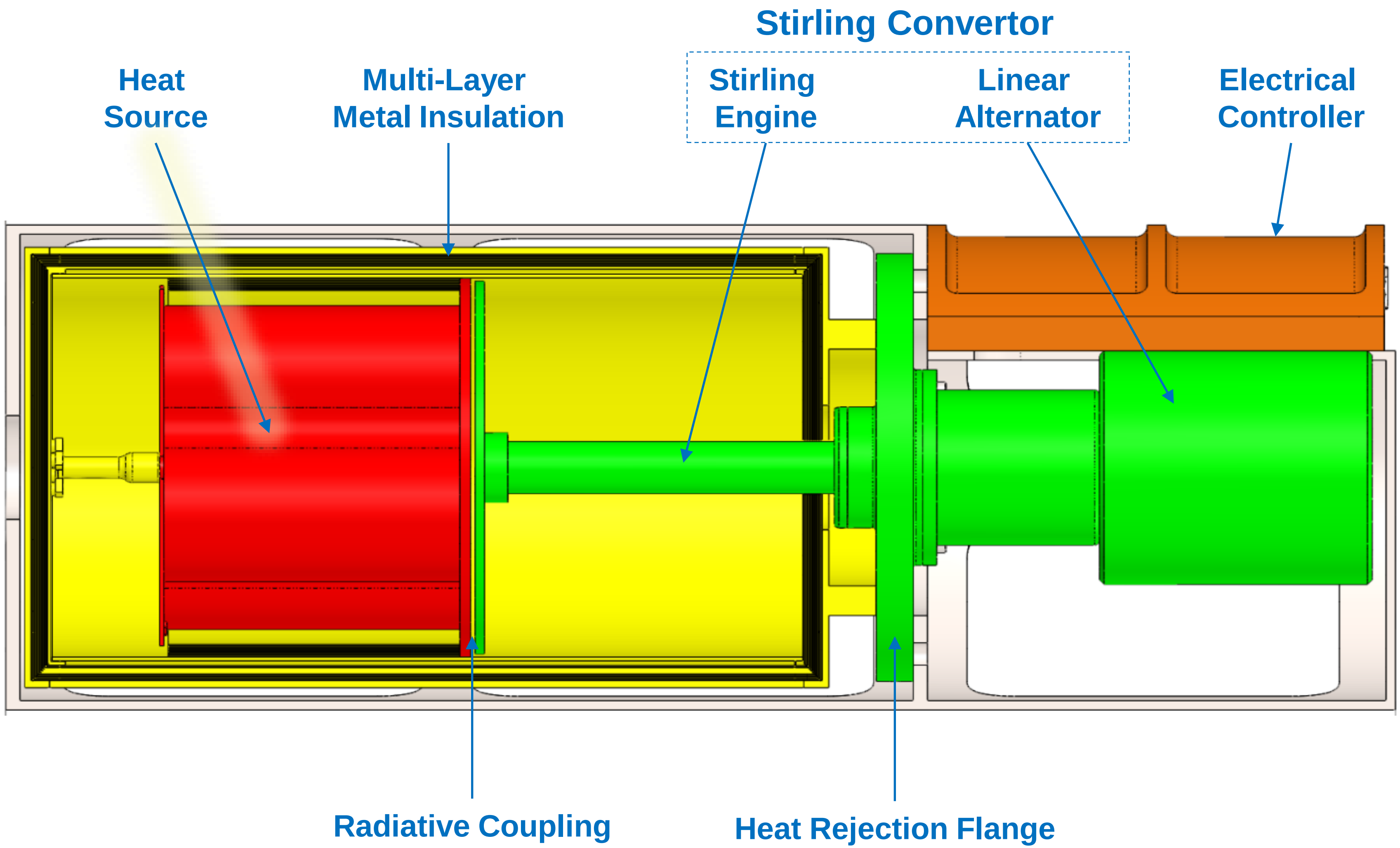
[Ref 1] Conceptualization of Seismic Monitoring Stations Being Deployed from Rover [***JPL Pub 04-10, Sept-2004]***

Low Power Dynamic RPS Concept

Design Goals

- Long life design (no wear mechanisms)
- 3 kg system mass
- Envelope of 11 cm diameter X 32 cm length
- Performance
    - Heat from multiple LWRHU
    - At least 1 We power output
    - At least 12% system efficiency
    - Maximum of 400 ºC acceptor temperature
    - Maximum of 50 ºC rejection temperature
- Robustness
    - Overstroke collision tolerant (limited time)
    - Operates in vacuum or atmosphere
    - Launch vibration
    - Constant accelerations
    - Shock
- Compliance
    - Minimize exported force
    - EMI

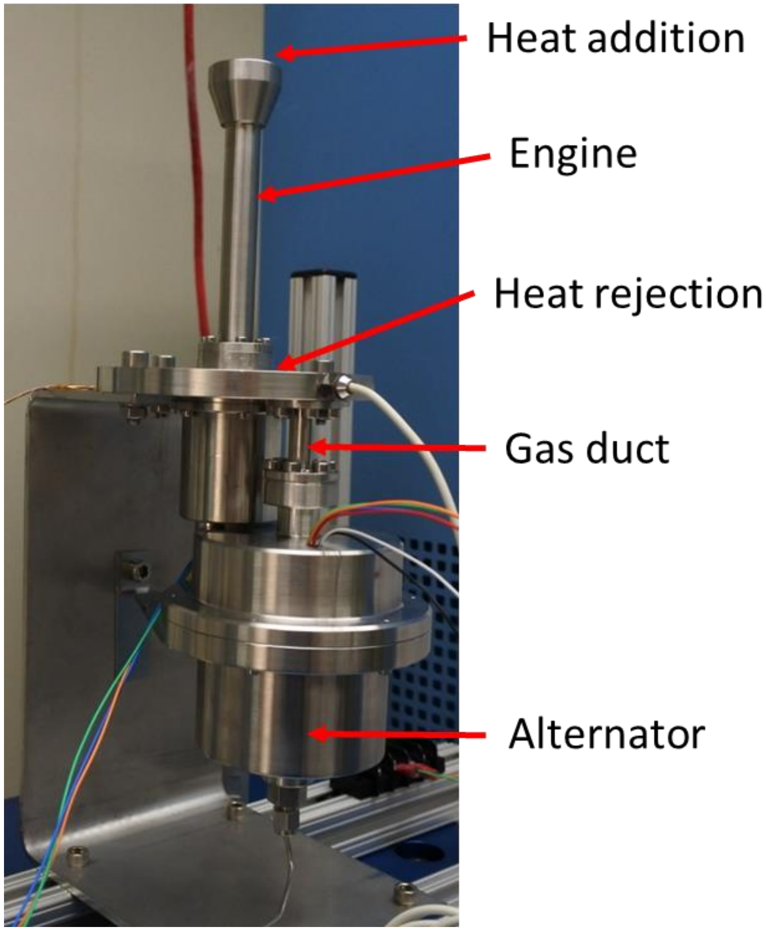
Low Power Dynamic RPS Concept



Stirling Convertor

Proof of Concept – 1 W_e design

- Split-Stirling, gas duct between engine and alternator compression space
- Gap regenerator – no porous matrix
- Flexure bearings for piston and displacer
- Laboratory design did not minimize mass
- Simulating heat from 8x RHUs using electric heater, 350 ºC hot end temp
- Fluid loop heat rejection, 50 ºC cold end
- 100 Hz, 94 psig helium, 4.0 mm X_p, 2mm X_d

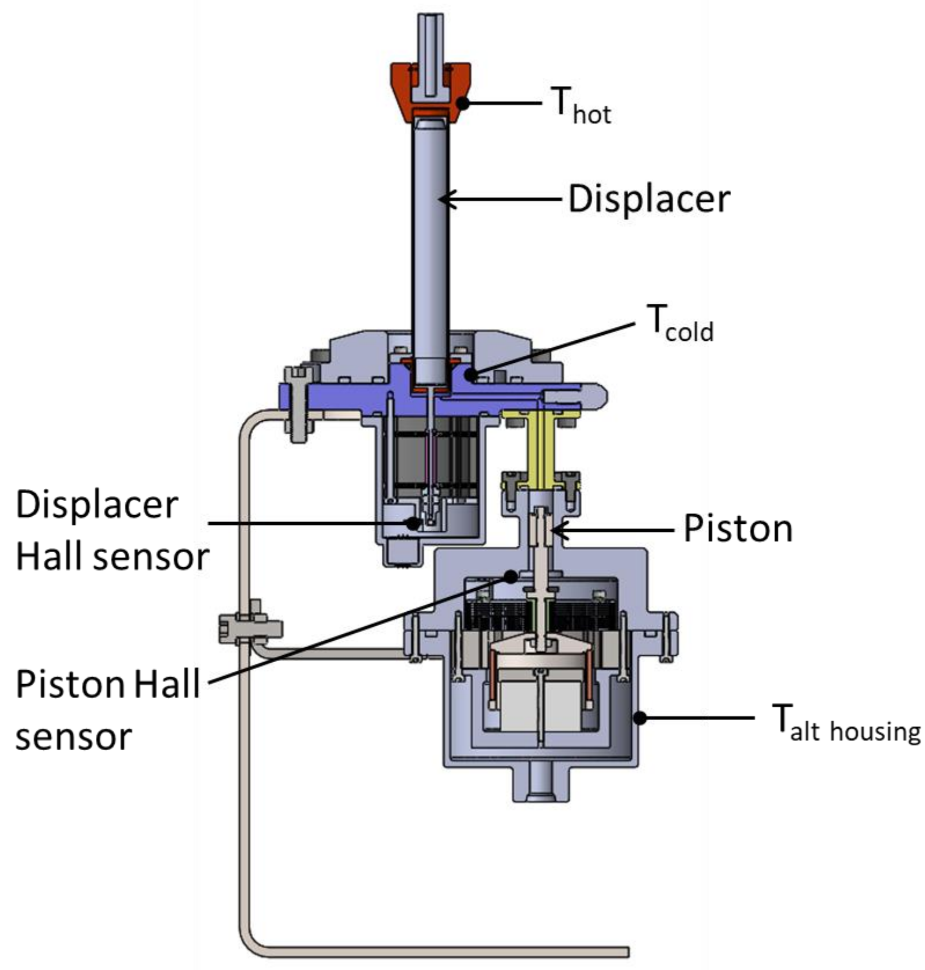


Test Setup
(insulation not shown)

Convertor Instrumentation

Instrumentation

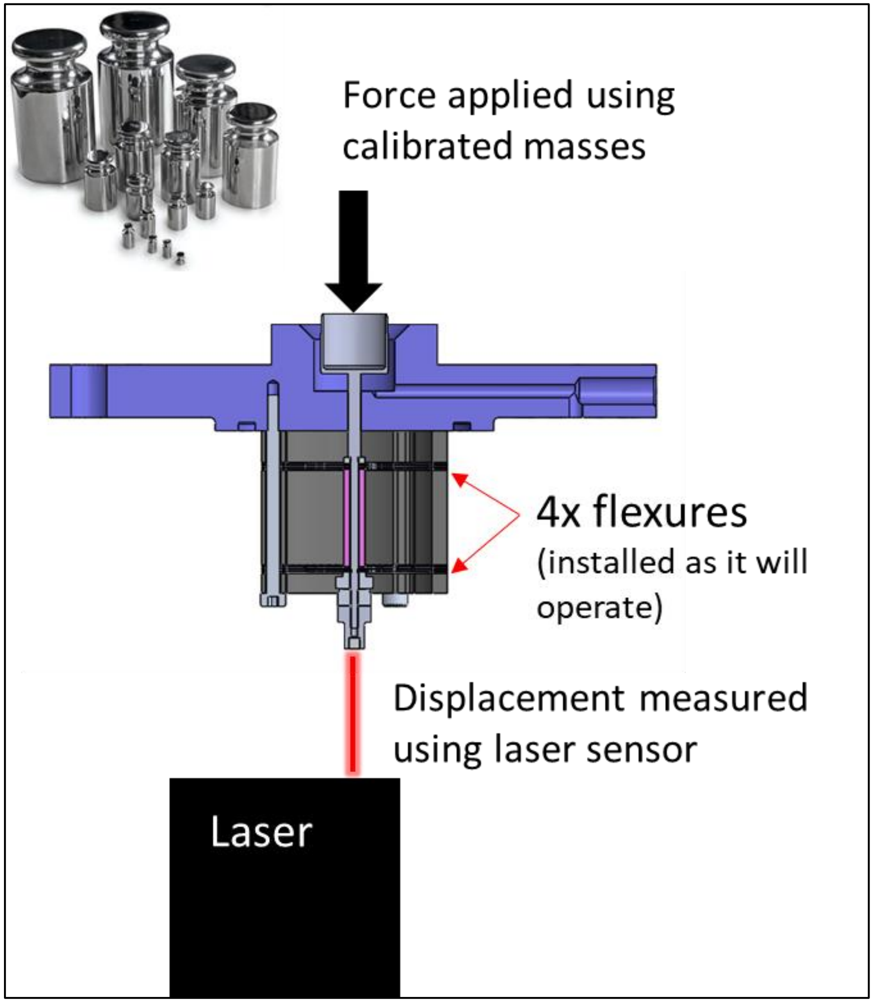
- Piston hall effect sensor
- Displacer hall effect sensors
- Dynamic CS pressure transducer
- Hot end temperature (1x)
- Cold end temperature (1x)
- Alternator housing temperature (1x)
- Electrical heat input
- Alternator output

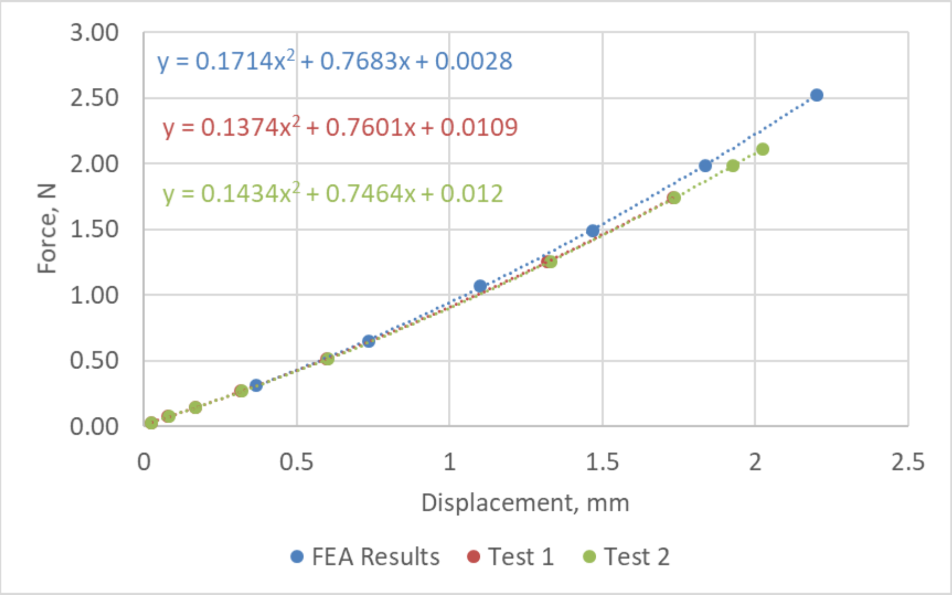


Testing Sequence

- Flexure Stiffness Characterization
- Displacer & Piston Resonance Characterization
- Displacer & Piston Position Sensor Calibration
- Convertor Characterization

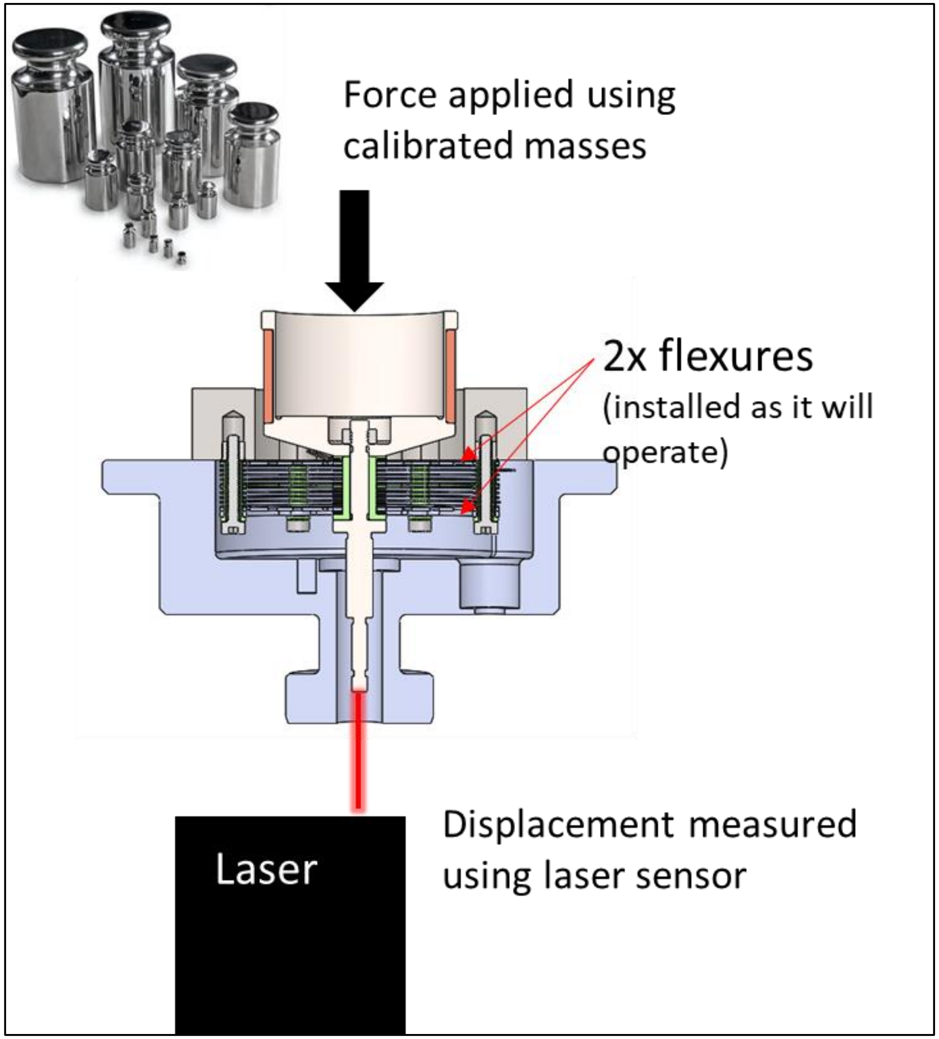
Displacer Flexure Stiffness Characterization

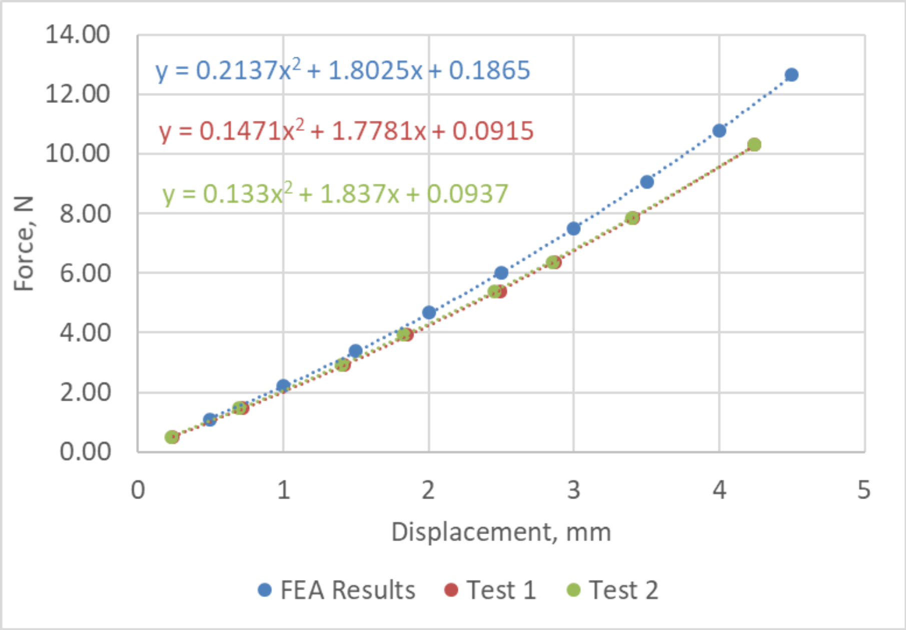




Finite element model over predicted displacer flexure stiffness by 7% at full 2 mm amplitude

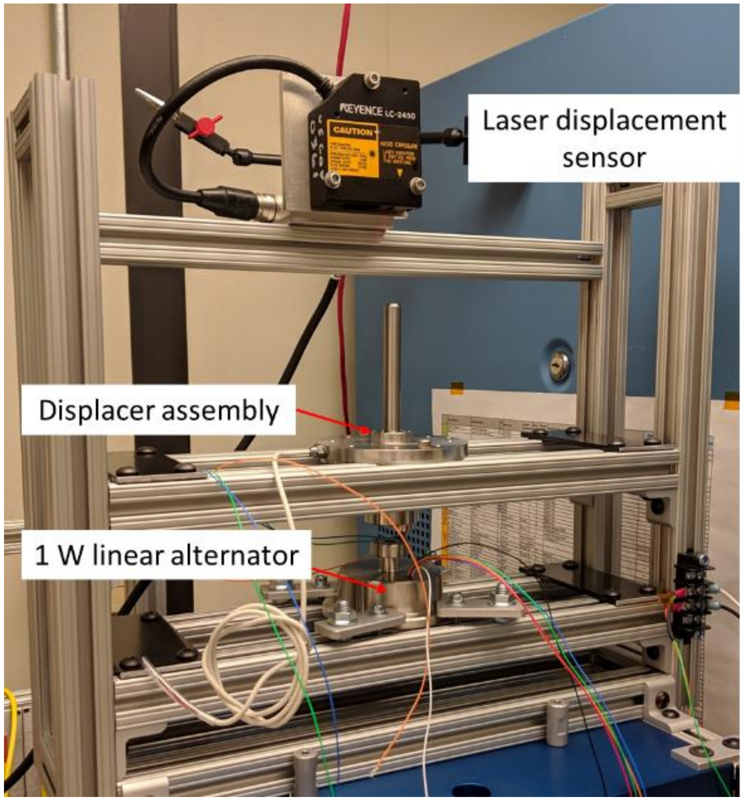
Piston Flexure Stiffness Characterization





Finite element model over predicted piston flexure stiffness by 13% at full 4 mm amplitude

Displacer Resonance Characterization

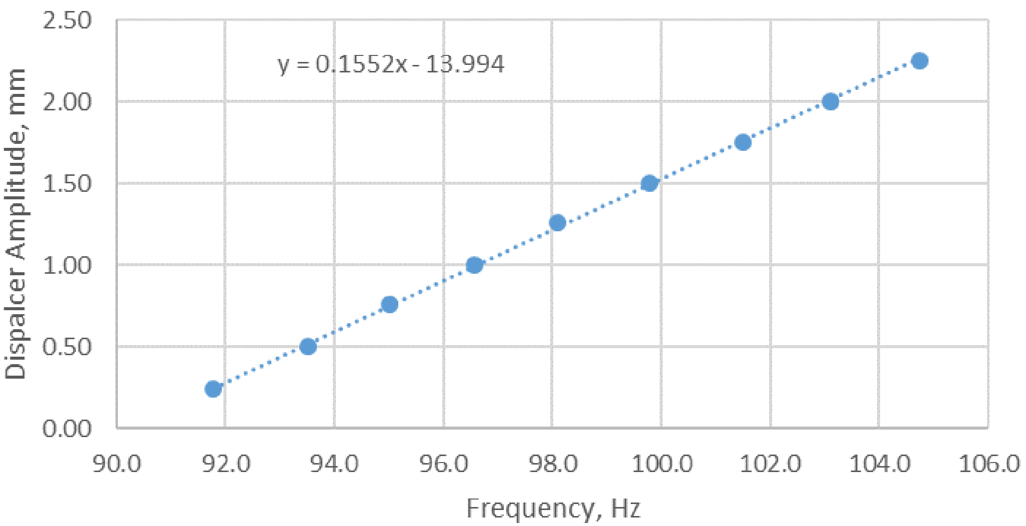


Test setup used for characterizing displacer resonance.

Goal: Achieve 102-103 Hz at 2 mm amplitude

Procedure:

- 1 W linear alternator was used as an exciter driven by an AC source
- Frequency swept from 90 to 104.75 Hz
- Displacer (mass-spring) assembly allowed to resonate
- Adjust number of flexures and mass as needed.



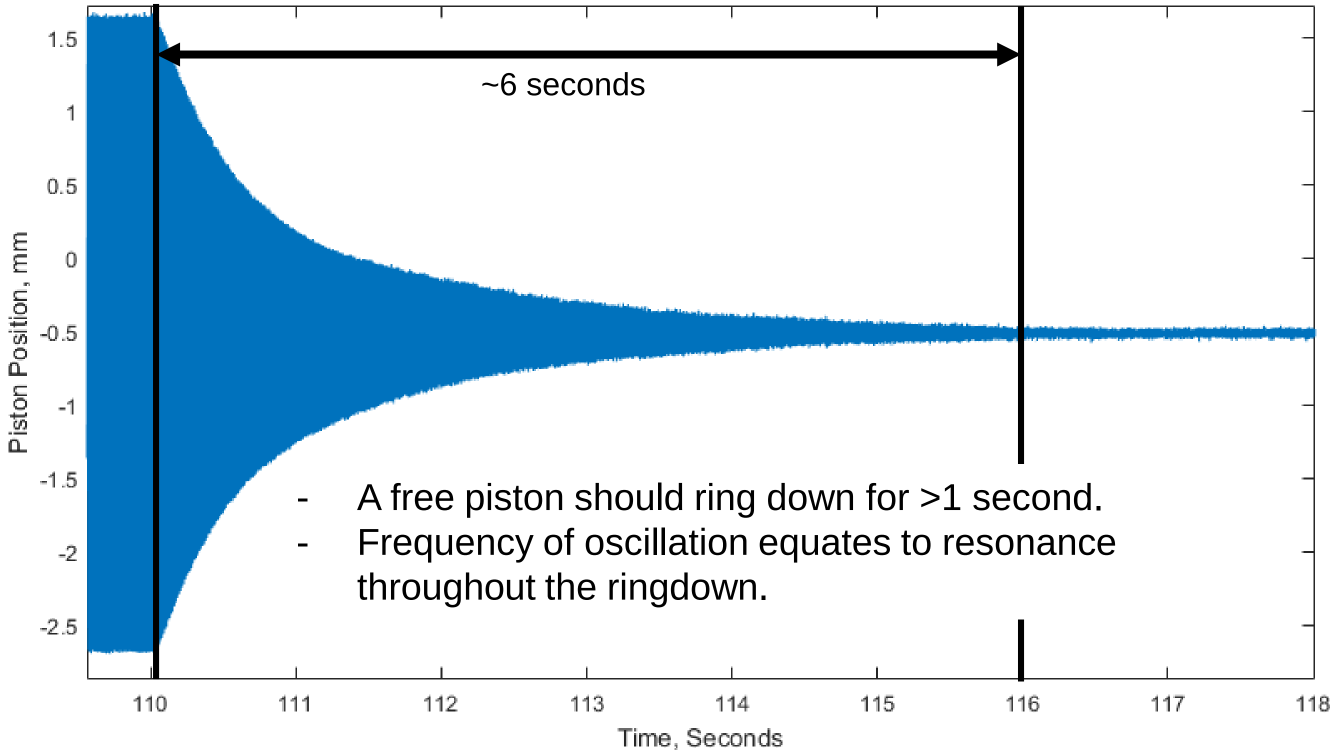
Displacer amplitude (X_d) versus frequency.

Piston Resonance Characterization

Goal: Achieve 95-98 Hz at 4 mm amplitude.

Two Approaches:

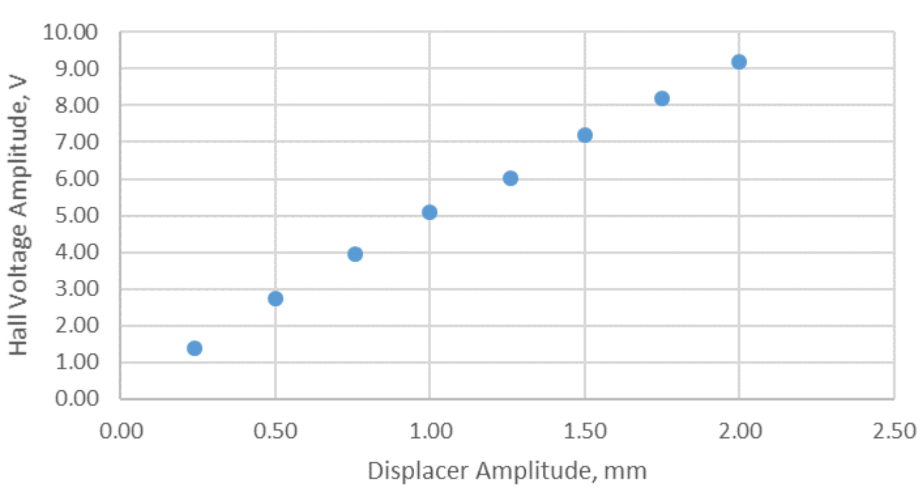
- Resonant approach (used for displacer), requires 2x alternators
- Ringdown
    - Drive alternator to 4 mm, go open circuit on the alternator.

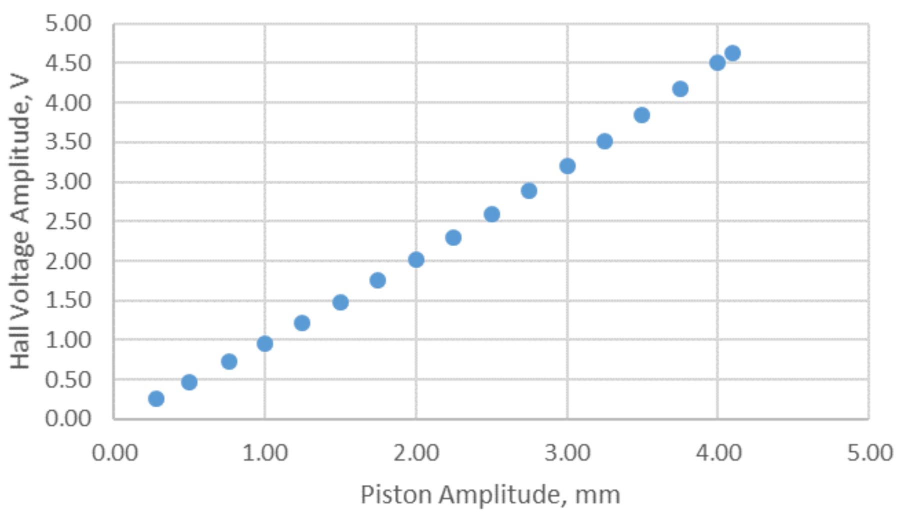


Displacer & Piston Position Sensor Characterization

Procedure:

- Displacer was excited via harmonic resonance.
- 1 W linear alternator was driven via AC source.
- A laser displacement sensor was used to measure position.
- All signals were recorded and monitored via LabVIEW.
- Correlations of hall sensor voltage amplitude to laser amplitude (in mm) were derived.



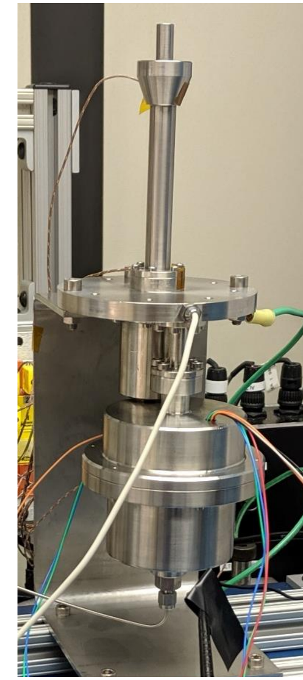


Signals are linear over and beyond entire operating range.

Convertor Characterization

Test process:

- Engine and alternator assemblies were integrated
- Convertor filled with helium
- Used and AC source to drive the piston
- Motor at piston amplitude of 2 mm at frequencies of 95-103 Hz
- Motor at piston amplitude of 4 mm at frequencies of 95-103 Hz



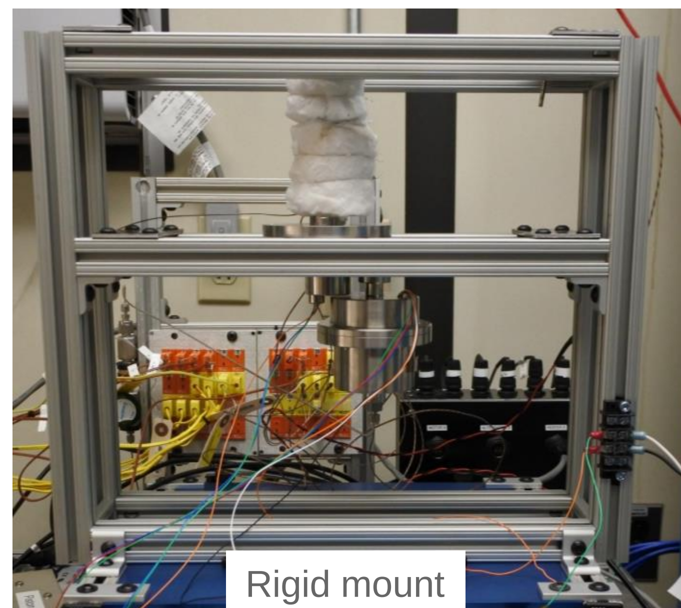
Non-rigid mount

Observations:

- Round 1 of testing w/ **non-rigid mount**

	Mode 1	Mode 2
Hot-end	Heating	Cooling
Xp-Xd Phase Angle	~170 deg	~0 deg

  - Measured case motion: 0.1 mm
- Round 2 of testing w/ **rigid mount**
  - Displacer leads piston by 50-80 degrees at frequencies of 95-99 Hz.
  - Cooling of hot-end observed
  - 3.5 W to drive the cooler (rub discovered)



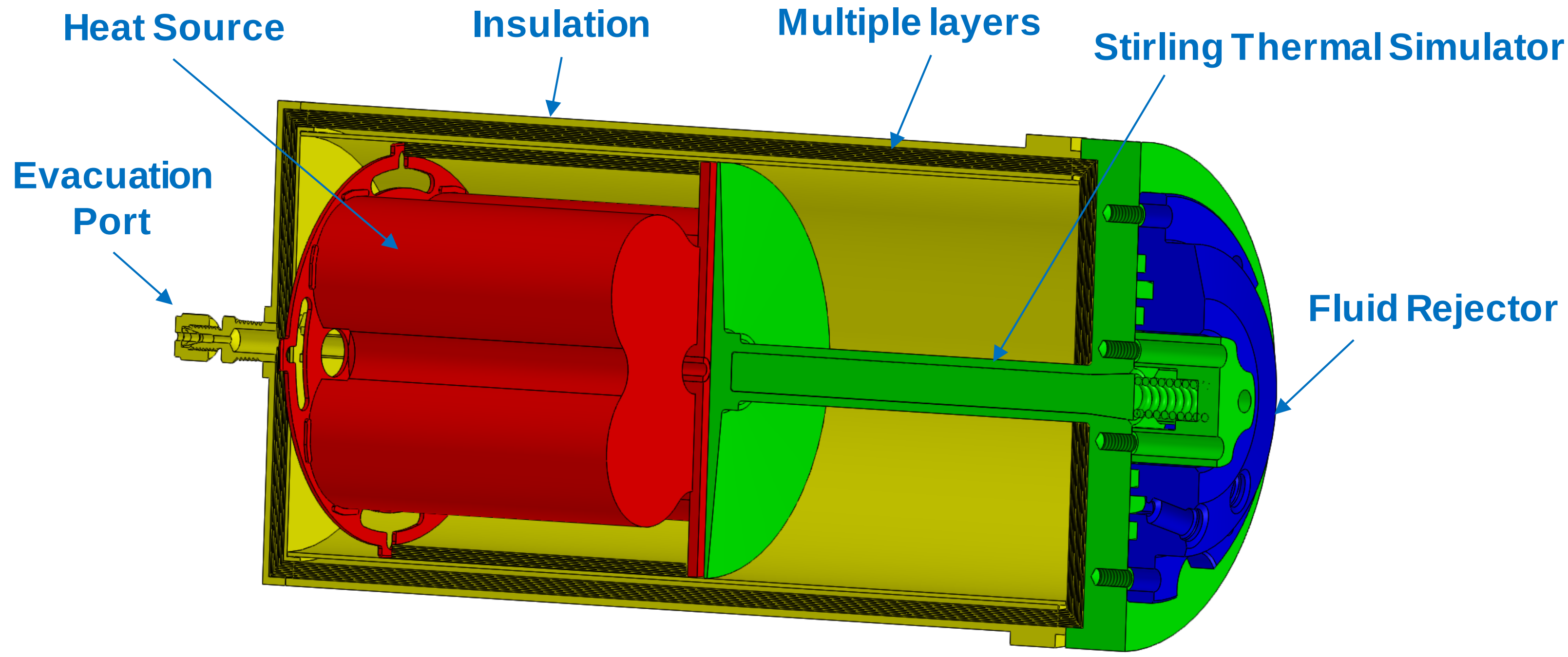
Rigid mount

Insulation – Functional Test

Objective: High performance required (~0.001 W/m-K effective thermal conductivity)

- Peregrine Falcon Corp. designed and fabricated multi-layered metal insulation (MLMI)
- The prototype is currently under test at GRC.

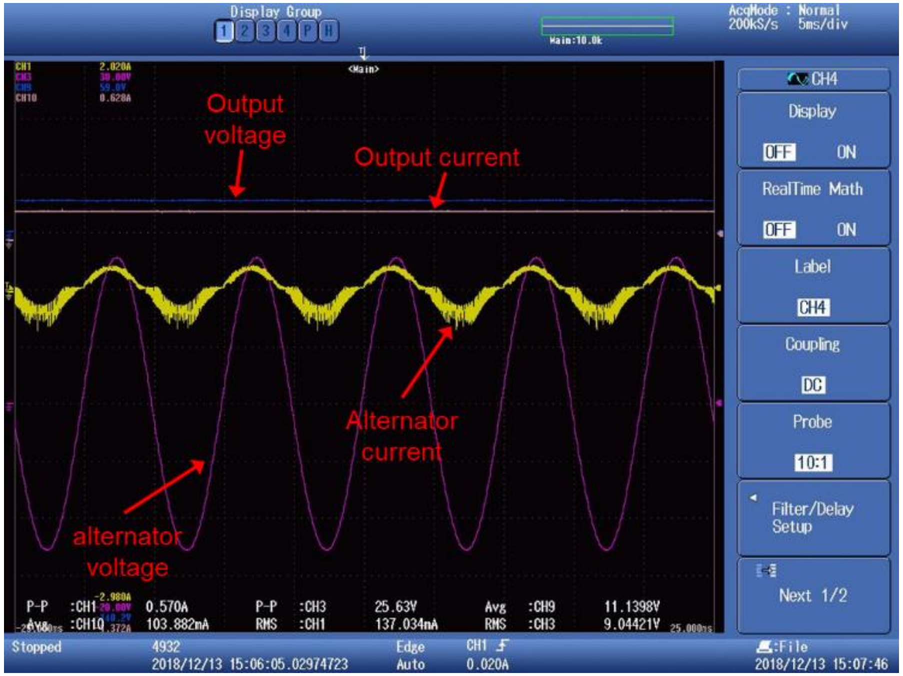
Current Challenge: Low conductance of the evacuation port requires long evacuation time.



Controller

Controller design and functionality

- Linear AC regulator controller using a MOSFET H-bridge with analog circuit to control FETs for AC to DC rectification and load control
- Constant power load monitoring allows for load control and shunting of unused power

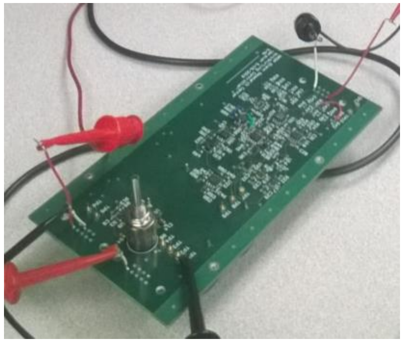


Design Progression

- LTspice model contains a linear alternator, H-bridge rectifier, constant power circuit, and waveform smoothing circuit for power factor and Total Harmonic Distortion correction
- Model validated with breadboard testing.
- Design finalized and incorporated into a printed circuit board design. Assembly in progress

Controller Breadboard Testing Results

Alternator Voltage, $V_{p\text{-}p}$	25.6
Alternator Power, W_e	1.24
Controller Voltage, V_{dc}	11.1
Controller Power, W_e	1.16
AC-DC Conversion Efficiency	93%



Summary

- Small RPS are being considered for small spacecraft missions
  - Enables long-life power for use in darkness
- 1-W Stirling RPS is in development at NASA GRC
- Testing & Demonstration of Subcomponents is Underway:
  - Convertor
  - High-performance insulation
  - Controller

Special thanks to contributors

- Barry Penswick
- Jonathan Metscher
- Malcolm Robbie
- Cheryl Bowman
- Paul Schmitz
- Roy Tew

Thank you for attending